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This report contains the recommendations for future research in scattering that were developed by eleven panels at the National Conference on Electromagnetic Scattering held at the University of Illinois at Chicago Circle in June 1976.

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P.L.E. Uslenghi (Editor)

RECOMMENDATIONS FOR FUTURE RESEARCH IN SCATTERING

Communications Laboratory Report 76-3

December 1976

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COMMUNICATIONS LABORATORY
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Preface

This report contains the recommendations for future scattering research as developed by the participants in the National Conference on Electromagnetic Scattering held at the University of Illinois at Chicago Circle on June 14-18, 1976.

The editor of this report wishes to thank all Conference participants for their contributions and in particular the Air Force Office of Scientific Research/NM (Program Manager: Dr. Robert N. Buchal) for its financial support of the Conference.

Piergiorgio L. E. Uslenghi

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INTRODUCTION

A National Conference on Electromagnetic Scattering was held in Chicago in June 1976 with the support of the United States Air Force Office of Scientific Research. The purpose of the Conference was to bring together researchers from Air Force, Army and Navy laboratories, from universities and from industry to discuss the present state of the art and future research developments in electromagnetic scattering, in order to maximize the usefulness of this research area to the development of effective aerospace systems. Three documents originated from the Conference: a volume of proceedings containing the summaries of some 80 invited and contributed papers, a book on Electromagnetic Scattering containing over 20 contributed chapters on selected topics of special interest, and the present report which contains the recommendations for future research in scattering that were developed by 11 panels of Conference participants.

The reports of chairmen of these 11 panels are here reproduced as submitted, with only minor editorial changes. Any attempt to generate an ordered list for future research in scattering out of the panels' recommendations would inevitably contain the bias of whomever generates the list. Thus, the editor of this report has refrained from rank ordering the research priorities indicated by the various panels.

There are some general recommendations which were agreed upon by a large number of Conference participants, either in discussions during the four-day Conference or in written inputs sent to the editor at a later time. It is appropriate to list these general recommendations in the following:

1. It was felt that insufficient interaction presently occurs between researchers in universities who are largely responsible for developing new scattering techniques and the users of these new techniques in government

and industrial laboratories. It was suggested that fellowships should be generated to allow university faculty (perhaps during their sabbatical leaves) to visit Air Force laboratories for extended periods of time, thereby interacting with their researchers and gaining a direct insight into the problems that the developers of aerospace systems are faced with.

2. It was felt by most Conference participants that conferences of the type organized in Chicago should be repeated at periodic intervals (perhaps every three to five years) at different locations around the country. A particularly attractive possibility would be to hold such a conference on a rotation basis among the Air Force laboratories.

3. Regarding the organization and the format of the Conference, the following prevalent remarks were made: the Conference should be held without parallel sessions; it should consist primarily of invited papers which would give an overview of the state of the art rather than dwelling on the solution of a particular problem; it should address other problems besides those addressed by the first Conference; the number of working hours per Conference day were judged to be excessive and ought to be reduced at subsequent conferences; the informal discussions which arose during various panels' meetings were thought to be quite useful.

PANELS COMPOSITION

Several participants in the National Conference contributed significantly to each of the panel recommendations, either in formal meetings or in informal discussions or by written comments. It is important to acknowledge other contributors as well. Some of the panel memberships are indicated below.

Panel on . . .

Antennas: C.T. Tai, chairman; W.F. Bahret; G. Franceschetti; R.W.P. King.

Application of Modern Mathematical Techniques to Scattering: C.E. Baum, chairman.

Asymptotics: L.B. Felsen, chairman; W.F. Bahret; R.N. Buchal; R.E. Kleinman; T.B.A. Senior.

Experimental Techniques in Scattering: W.F. Bahret, chairman; C.H. Krueger, Jr.; C.A. Mentzer; V. Pyati; G.A. Taylor.

Hybrid Techniques Involving Combination of Asymptotic and Numerical Methods: R. Mittra, chairman; W.D. Burnside; R.G. Kouyoumjian; C.H. Krueger, Jr.; C.A. Mentzer; K.M. Mitzner.

Inverse Scattering: V.H. Weston, chairman; N. Bleistein; J.K. Cohen; J.R. Huynen; S.N. Karp; A.A. Ksienski; H.E. Webb, Jr.

Numerical Methods: R.F. Harrington, chairman; C.L. Bennett; C.M. Butler; W.A. Davis; E.K. Miller; R. Mittra.

Propagation in Random and/or Nonlinear Media: N. Marcuvitz, chairman; I.M. Besieris; A. Ishimaru; V. Twersky.

Remote Sensing of Environment: A. Ishimaru, co-chairman; J.R. Wait, co-chairman.

The State of the Art of Singularity and Eigenmode Expansion Methods: C.E. Baum, chairman.

The Use of Computers in Scattering: E.K. Miller, chairman.

PANEL ON ASYMPTOTICS

Chairman: L.B. Felsen, Polytechnic Institute of New York.

Asymptotic techniques are intended to deal in an approximate manner with complicated radiation, propagation and diffraction problems that cannot be solved exactly by currently available analytical methods. Whether in the high or low frequency regime, asymptotic procedures usually involve the delineation of tractable "canonical problems," which approximate the essential features of the given problem as closely as possible. The choice of the "best" canonical problem is essential to the success, accuracy and efficiency of asymptotic procedures. Therefore, a principal future task of asymptotics is to broaden the base of canonical constituents, which are presently employed.

At high frequencies, this implies a generalization of the geometrical theory of diffraction (GTD) to involve local wave types (new ray species) which take into account some composite feature of the physical configuration. Examples are surface rays on periodic or quasi-periodic structures, rays descriptive of local modes in waveguides or ducts with variable cross section, and rays descriptive of evanescent fields. For application to composite scatterers, where several of these wave types may exist simultaneously, the ability to convert from one to the other is essential. For example, scattering by a large open cavity with interior loading, such as an aircraft jet engine, involves as one of the constituent problems the excitation of whispering gallery modes in the concave interior by edge discontinuities, which can be analyzed in terms of conventional GTD; needed therefore is the conversion from edge diffraction rays to whispering gallery modes.

Asymptotic theories generally fail for certain parameter ranges in "transition regions" wherein the assumed basic field constituents, even when corrected by inclusion of higher order terms in the expansion, are inadequate

to describe the transition field. It is then necessary to employ improved "uniform" field types from one side to the other. These transition functions may be reducible to known and tabulated functions such as Airy functions, Fresnel integrals, or parabolic cylinder functions, or they may require the tabulation of new functions such as the Fock function for the high frequency shadow boundary behind a smooth convex object. With the development of new asymptotic expansions, there will emerge the need for new uniform representations. Numerical evaluation and tabulation of new transition functions, which are usually defined by integrals, is readily accomplished with modern computer facilities. At high frequencies, uniform representations may be constructed by use of the physical theory of diffraction or by spectral representation of the diffraction field. Each of these methods deserves further study to establish their versatility, utility and accuracy. In addition, consideration should be given to improved ways of continuously traversing transition regions, not by even more complicated formulas which, though correct in special cases, fail in others, but by constructive attacks on the asymptotic solution of the boundary value problem using, for example, an integral equation formulation.

A major problem besetting asymptotic techniques is the accuracy of the result provided by an asymptotic calculation carried out to a given order in the asymptotically small parameter (for example, k at low frequencies or (1/k) at high frequencies). Since tight analytic error estimates are not available, comparisons must be performed either on special configurations for which exact solutions and calculations can be provided, or on other configurations which can be handled by numerical techniques. By performing various such comparisons, one builds up the level of confidence in using, say, the leading term in the expansion for ranges of the asymptotic parameter which reach even moderately

large values. However, such practice must be accompanied with caution when the given configuration departs substantially from the one for which the comparison was made.

Composite scatterers at high frequencies give rise to multiple diffraction. The temptation exists to seek improvement of lowest order primary diffraction results by including multiple diffraction. Apart from the fact that multiply diffracted fields usually have a very complicated form, there is no guarantee that their inclusion via primary field interactions, which ordinarily are accurate only to a low asymptotic order, will furnish successive improvement. This aspect requires detailed further study.

Instead of pushing for increased accuracy in high-frequency diffraction by performing the asymptotic analysis to higher order, it may be preferable to extract lowest order dominant contributions from the exact field as formulated, for example, by integral equation methods, and to employ numerical techniques for the difference field. Such hybrid procedures deserve careful study since the extraction of the dominant asymptotic behavior should substantially improve the efficiency of the numerical evaluation.

There are two general comments that should be made concerning high frequency asymptotics. It must be recognized that even today there is no proof that any high frequency approach yields a result which is asymptotic in a rigorous sense for an arbitrary scattering shape. Though limited progress has been made in certain scalar cases, no firm mathematical foundation exists for the general scalar problem let alone the electromagnetic one. There is also the need for more precise error estimates with asymptotic formulas. It is one thing to claim that the difference between an exact and an asymptotic formula vanishes as some parameter goes to zero or infinity, but quite another to bound the expression for finite values of the parameter.

However, this is just what is required if asymptotic approaches are to give reliable results numerically.

At low frequencies a major problem is to extend the range of validity of the asymptotic results. In three dimensions where the fields are analytic functions of k, this requires finding an effective way to analytically continue the solution, preferably by some method which does not entail a knowledge of all terms in the low frequency expansion for each order of the continued expression. Integral equations provide a possible framework within which to work and to choose the 'best' integral equation may then require quantitative information about the spectrum of the integral operator. This in turn leads to the fundamental problem of determining the resolvent operator. If one can determine the pole (and its residue) of smallest magnitude (in k) of the field, the low frequency expansion can be continued analytically. Since the pole is essentially one of the resolvent and corresponds to an eigenvalue of the operator, it appears that low frequency asymptotics and the spectrum of the original operator are intimately related.

The general considerations above should be implemented on problems determined by present needs in the user community. A list of such problems is given below.

A. Radiation and Diffraction

1. Backscatterer and bi-static calculations at long and short wavelengths for target identification and echo control.

   a) structures with apertures and interior loading (aperture antennas, engine air ducts, etc.),

   b) disk antennas, corner reflectors, etc.,

   c) highly complex targets such as airplanes, etc.,

   d) effects of non-metallic and coated surfaces,

   e) radar signatures from chaff,

f) radar signatures from the ocean surface.

2. Antennas

a) coupling between an antenna element and mounting structure at low and high frequencies,

b) mutual coupling between elements on complex bodies,

c) antenna element design taking into account a) and b).

3. Relation of 1. and 2. to the EMP problem.

4. Optics

a) design of laser cavity mirrors in the presence of active and passive lasing materials,

b) fiber optics (propagation and coupling problems).

B. Propagation

1. Loran C propagation over real earth,

2. Ionospheric effects.

3. Induced fields on satellites moving through striated plasmas

C. Inverse Problems

1. Target re-construction from sampled echos.

2. Ionospheric sounding.

3. Adaptive techniques for sampling requirements.

D. Non-linear effects on EM fields in propagation and scattering.

While the areas listed above cover a wide range and therefore require analytical models of various kinds, a few basic problems can be identified. Item A 1.a deals with the effects of open cavities with interior loading or interior structure. This involves excitation of, propagation on, and scattering from concave surfaces, and the interaction of fields on concave surfaces with perturbing structures on or near the surface. The concave surface problem also arises in item A 1.b. Item A 1.c requires treatment of

curved and intersecting edges, fins, etc. Item A 1.d requires study of a whole new class of canonical problems, i.e., extension of GTD, for example, to coated objects. Coatings are to be modeled either by actual layers or by surface impedances when justifiable. Items A 1.e and A 1.f require scattering from multiple targets with regular (periodic) and random spacing.

The same general considerations as in item A 1 also apply to item A 2. However, the presence of multiple elements, as in antenna arrays, suggests generalization of GTD, for example, to periodic and quasi-periodic structures. Item A3 is covered elsewhere in this report and will therefore not be addressed here. Let it merely be noted that the relation of the singularity expansion method to target identification and discrimination is a subject of importance. This enters also into item C.

Item A 4 involves combinations of GTD and guided wave tecaniques for ray and beam fields. Effective methods here are evanescent wave tracking and complex-source-point techniques for generation of beam solutions from Green's function.

Item D is being addressed elsewhere in this report.

Item B involves assessment of various environmental factors on propagation. Here, emphasis has to be placed on realistic models before calculation is attempted. This calls for further development of high frequency and low frequency asymptotic methods accounting for losses, variable ground features, etc.

It is evident from the listing above that the need is for attacking <u>real</u> problems which cannot always be idealized by models amenable to analysis. Therefore, the previously mentioned interaction between analysis and numerical methods is essential for the successful solution of these problems. However, careful judgement should be exercised concerning the stage at which the computer enters the picture. This opens up a fertile area of exploration.

PANEL ON NUMERICAL METHODS

Chairman: R.F. Harrington, Syracuse University

During the recent National Conference on Electromagnetic Scattering a number of suggestions for further research on numerical methods were made. A committee of six members was formed to help identify those areas for which further research appears to be needed. Many specific problems were mentioned by the various members, but the list is too long to include in this report. Only those general topics suggested independently by two or more committee members are listed here.

1. Further work on the combination of moment methods with other techniques, such as asymptotic methods is needed. A particularly promising approach appears to be the use of transform methods, such as in the spectral theory of diffraction. Closely related to this is the incorporation of the proper asymptotic behavior of the current at edges and vertices in the moment method.

2. Further development of numerical methods to treat problems involving dielectric and other penetrable bodies is needed. This can be either via a differential equation, as in the unimoment method, or via an integral equation, as usually done in the moment method. Also, extension of solutions to larger bodies would be desirable.

3. Further study of computational methods for aperture problems is recommended. Again, there are several numerical approaches to the solution, which can be classified broadly into the differential and integral equation methods. Moreover, solutions can be obtained either in the frequency domain or in the time domain.

4. More efficient methods to treat radiation and scattering in the vicinity of imperfect ground planes would be desirable. The present methods used are either the Sommerfeld integral, which is time consuming, or the reflection

coefficient, which is not applicable for bodies very close to the ground plane.

5. Numerical solution of composite problems, such as those made up of both conductors and dielectrics, should be investigated. For low to intermediate frequency solutions, the various moment methods appear promising. For higher frequency solutions, the asymptotic methods, perhaps combined with the moment method would be appropriate.

6. A study of estimation procedures for upper bounds, median values, errors, etc., for guidance in the development and use of numerical solutions would be desirable, especially in a statistical framework. After such estimates are available, studies of existing solutions could be made comparing them as to accuracy and efficiency.

7. Development of a set of standard problems for comparison and evaluation of alternate and new numerical methods would be worthwhile. This could probably be done in conjunction with other research, and would not require a separate project.

PANEL ON HYBRID TECHNIQUES

INVOLVING COMBINATION OF ASYMPTOTIC AND NUMERICAL METHODS

Chairman: R. Mittra, University of Illinois

There are three basic approaches to deriving high frequency asymptotic solutions of electromagnetic and acoustic scattering problems. First of these is the Geometrical Theory of Diffraction, or GTD, which is based on a ray optical interpretation of the scattering phenomenon. The second is the Physical Theory of Diffraction, or PTD, which is formulated from a diffraction theory point of view. The third, STD, or Spectral Theory of Diffraction, involves the use of a plane wave representation of the fields. Included in this report are directions for future research aimed at combining these asymptotic techniques with numerical methods. Some of the problems that deserve attention are listed below.

1. Solution of new canonical problems that would lead to improved GTD parameters, e.g., diffraction coefficients, launching coefficients, attenuation constants, etc. A few examples of these problems are: plane surfaces bounded by intersecting edges; edge illuminated by a source close to it where the radial component of the incident field is important; higher order solution for diffraction by concave surfaces; combination of GTD with moment methods.

2. New diffraction results based on rigorous formulation as in the Physical Theory of Diffraction; documentation of the basic PTD concepts; understanding of multiple scattering effects from the integral formulation; Fresnel region scattering.

3. Improve 'Believability" of solutions by providing reliability accuracy checks and error estimates. Provide methods for systematic improvement of zero-order or first-order asymptotic solutions by coupling the

asymptotic methods with integral equation techniques, as for instance, in the STD method.

4. Accurate solution of various aircraft parts that cannot be modeled using simple canonical structures. Examples are:

a. jet engine intake ducts including the termination at the engine face

b. jet engine exhaust cockpits

c. aircraft cockpits

d. radar antenna

e. radar compartment including equipment boxes

f. corner reflector geometries (such as wing-fuselage junction or missile fins)

g. impedance boundary problems and lossy coatings

h. rounded and blund edges

5. Development of efficient input/output systems which would provide low cost, versatile and efficient description of the geometries of complex structures for use with computer codes for high or low frequency solution of scattering problems.

PANEL ON THE USE OF COMPUTERS IN SCATTERING

Chairman: E.K. Miller, Lawrence Livermore Laboratory.

I. Introduction

Computer use in EM scattering has in recent years increased at a pace determined both by developments in computer technology and by computer-inspired advances in numerical and analytical techniques. It is in fact difficult to identify an area in electromagnetics that has not benefited from these developments. Even those EM sub-disciplines such as various asymptotic techniques, that are not so obviously computer oriented as the method of moments, heavily rely for their eventual practical application upon computer availability. In any case, the net result has been to significantly increase the technological productivity of EM problem solvers.

As is not at all uncommon in such circumstances, problem complexity has more than kept pace with the developing problem-solving capability. This situation naturally enough can lead to a certain amount of frustration on the parts of both the technologists who develop the technology and of the users who generate and solve the problems. The result can be a perceived lack of progress, and uncertainty about the role of computers in EM. It was the purpose of the panel to assess this topic as seen by representatives of government, academia and industry. A summary of observations which arose during the discussion are included in Section II below, and some specific recommendations to address identified deficiencies are made in Section III.

II. Summary of Panel Discussion

In order to provide a framework for the discussion to develop, the

following list of questions was submitted by the chairman to the panelists:

1. In what specific areas have computers had the greatest impact? The least impact?
2. What do you feel are the most important ingredients of user-oriented codes? Or, what does user-oriented mean to you?
3. In what ways do presently available codes satisfy question 2? In what ways are they deficient?
4. Concerning needs you are aware of, what are the most serious limitations of current computer techniques? Do you have suggestions for circumventing any of them?
5. In what ways can computed results be validated, and/or error bounds established, not only for new codes, but for working codes regarded as reliable?
6. How can computers be most effectively exploited? For example parameter studies; data base development; to gain physical insight; etc.
7. What can and should be done to improve technology interchange in computer usage?
8. In what areas do you expect the most significant developments in computer use for EM scattering in the next 5-10 years?

In response to the above, and other comments, observations and questions that came up during the discussion, several distinct, but related aspects of code usage were found to be of concern. They are:

<u>Code-related issues</u>

Computer codes of course play a central role in computer use in electromagnetics. There are consequently numerous aspects about codes which

concern both technologists and users. Among these are the following.

1) Standardization. This includes both some standardized format with respect to comment cards, code notation following that in the documentation, etc. and the possibility that a smaller number of standard, "polished" codes might be preferable to the wide variety of, for example, wire codes now in use.

2) Documentation. There was general agreement that code documentation is extremely inconsistent in quality and quantity, and that its inadequacy significantly detracts from code transferability.

3) Test cases. Establishing that a code is working properly is not easy. The use of test cases to confirm that computed results are reliable might be considered. These test cases might serve as internal consistency checks to show that the code is reproducing earlier results, as well as external checks to demonstrate the credibility of the computed results.

4) Interchange. Much code duplication takes place because previously developed codes are unavailable, not user-oriented or poorly documented. Code accessibility is of paramount importance in interchanging code technology. One example of a mechanism for code dissemination is the Lawrence Livermore Laboratory Computer Code Newsletter. Its effectiveness is largely due to the involvement of knowledgeable technologists in the collection, evaluation and documentation of the codes, and who supply de-bug help and advice at no cost.

5) Use awareness. By their very nature, codes are limited in what they can do. User disappointment often stems from misapplication due to lack of awareness concerning this fact.

<u>Government's Role</u>

Almost all code-development work in electromagnetics is government sponsored.

But generating the need and funding the work should not constitute the government's entire responsibility in this area. Additional attention in the procurement cycle to items relating to code activities could begin to alleviate some of the problems listed above. As a matter of fact, without active government support and direction, it is likely that little progress will be made however.

Technical Directions

A wide variety of computer-related analysis techniques have become available in recent years. Their development, for the most part, has occurred in a rather uncoordinated way in response to specific problem needs. More recently, the possibility of developing hybrid techniques to obtain capabilities beyond those offered by any single approach has been explored. Some discussion has also taken place regarding alternatives to strictly pessimistic deterministic methods, based on probabalistic concepts where the applications permit. From a still more general viewpoint, the possibility of developing a methodological framework which would provide guidance in the development and application of all the tools at the user's disposal has been debated.

Applications

The greatest diversity of opinions regarding computer use in electromagnetics arises with respect to applications. This situation is due to not only the variety of problem types that are encountered, but the wide range of what constitutes acceptable results, depending upon the particular needs perceived by the user. Topics discussed included:

1) Accuracy. Perhaps the most common concern is accuracy of the computed

result. To some, the cost of a calculation is of secondary importance, so long as the results are accurate. But accuracy can be difficult to define because the computer-model results may be numerically valid, but have little relation to the physical problem of interest. Credibility of the result for the given application is the key issue.

2) Model detail. Most calculations require a tradeoff between model detail which influences accuracy, and resources such as programming time, computer cost, etc. required for the calculation to be performed. There presently seems to be little guidance available to the user concerning tradeoffs between accuracy and cost.

3) Calculation detail. The amount of information obtained can significantly influence the costs associated with the calculation. There is a tendency to overkill the problem when in doubt.

4) Interpretation of results. When used effectively, computer models can provide a great deal of insight regarding electromagnetic phenomenology. However, this capability, to be exploited, needs some thought and attention on the part of the user. Many EM studies unfortunately exhibit little effort in this direction and so may not realize the full potential of the computer in this role.

5) Problem types. At the risk of oversimplifying, technologists tend to study simple problems in great depth while users by contrast study more complex problems in less detail. The most important reason for this is the typical need on the user's part to do quick reaction studies, perform systems tradeoffs where EM characteristics are but one of many factors involved, etc. while dealing with real-world problems. Air Force problems naturally include aircraft RCS where the complex geometry, engine ducts, RCS reduction, etc. provide a real challenge. Computer techniques provide

part of a set of tools which, including experimentation, are used in an attempt to achieve specific design goals.

III. Recommendations

As a result of the panel discussion outlined above, the following recommendations are made to the Air Force.

A. Computer-code information exhange should be expedited by establishing and implementing:

1. Standard procedures for the delivery of codes developed under contract, including minimum requirements for documentation and comment cards, delivery period, validation test cases and follow-up assistance.

2. Distribution procedures to provide access to codes, documentation and application's guidance.

3. A user-experience data base, to make available in a concise, standard format, summaries of applications results, including both positive and negative aspects of the calculation.

B. Technical areas to be emphasized should include, but not necessarily be limited to:

1. Development of hybrid methods to more effectively exploit the advantages of the separate approaches.

2. Assessment of the possibility for developing probabilistic and estimation procedures to obtain, for example median values and probability distribution of RCS, upper bound limits on induced currents, etc.

3. Development of realistic accuracy requirements and modeling guidelines to reduce numerical overkill and excessive computation.

4. Initiation of the development of an overall methodology for EM problem solving.

PANEL ON EXPERIMENTAL TECHNIQUES IN SCATTERING

Chairman: W.F. Bahret, Air Force Avionics Laboratory.

For producing hard data on scattering or radiation from arbitrary bodies, the work-horse today is usually an experiment. From elementary components to major measurements systems, hardware has been developed to perform many types of sophisticated measurements, often with completely automatic operations and production of near real-time results. Techniques for indoor (anechoic chamber) and outdoor (large scale range) static measurements are well advanced, with numerous facilities in operation. Dynamic measurements have kept pace, in the sense that sophisticated capability is available in selected facilities. Unfortunately, these facilities are generally dedicated to specific tasks, such as ballistic missile testing, and have not been available for many more mundane needs, such as chaff evaluation.

Despite the many good things which can be said about capability vis-a-vis operational needs, there are two major problems which require further effort to expand capability. The first of these has been long standing, and has been the impetus for periodic surges of development effort in the past, i.e., it is not uncommon for operational radars (for example) to be based upon use of scattering properties for which there are little or no data, and for which capability to provide data is minimal. An example of this curious situation is an ultra-high resolution (in 3-D) radar planned for reconnaissance use. There is no experimental facility capable of providing scattering data applicable to such a radar. All too often, baseline data needs are satisfied <u>after</u> an operational system is in advanced stages of development.

The second problem urging expanded measurement capability is based on increasing requirements for design of the scattering bodies themselves, whether

large complex vehicles or small chaff elements, to provide specific scattering properties. Fundamental to such designs are the understanding of scattering mechanisms which permits their control, and the evaluation of effectiveness of the designs. The former requires improved diagnostic capability, while the latter necessitates the measurement of exotic, and perhaps time-varying, properties of a scattered electro-magnetic signal.

Beginning with diagnostic measurements, one must recognize that present capability resides mainly in two areas - surface probes for determining current distribution and measurement of scattered fields from gross geometries or parts thereof. Impulse techniques have been investigated in a few cases, but the state-of-the-art is too elementary to receive serious consideration as a routine diagnostic tool in the near future.

Surface probes provide very useful data with acceptable accuracy when carefully implemented. However, most applications to data have been to simple and basic geometries which pose minimal problems to use of the probe. Since insight gained from probe measurements has been the basis for many significant advances in coping with scattering phenomena, it would seem that even greater advantage could be taken of results for more complex bodies, such as open-ended cavities (jet intake for example). A paper at the Conference demonstrated the difficulty in predicting intake echo, largely because the important scattering mechanisms are elusive. Clearly, the ability to define the fields on both metallic and dielectric surfaces of such geometries would be invaluable. The payoff from more capability should be great.

Measurement of total scattering from bodies necessitates an iterative process which is often lengthy and expensive when definition of contributors is required. One measures, changes, analyzes, changes, etc., etc., before scattering mechanisms are understood to the point where control is possible.

Nevertheless, this process has been the basis for the rather advanced state-of-the-art in signature control which exists today. Short of providing instrumentation capable of resolving scattering sources with dimensions in the order of a few centimeters (in three dimensions) there does not appear to be much possible in the way of improving scattered field measurements for diagnostic purposes. Such an ambitious goal (high resolution) is not entirely out of the realm of possibility with today's technology, however.

Turning next to static measurements, as mentioned earlier there exists a capability which satisfies many of the operational needs today. Both for antenna radiation and body scattering, it is possible to produce most of the far field data needed for effectiveness evaluation. Moreover, near field techniques have been demonstrated and in a few cases put to routine use in providing data for that region where parameters vary with range. Unfortunately, large scale implementation of near-zone facilities for large body measurement has not been initiated, partly because of cost and partly because requirements, though important, are much fewer than for far-zone data. Because scattering (radar echo) needs are usually more complex than any for antenna radiation patterns, there is one area where improved instrumentation would be of great significance - namely in providing good three dimensional resolution of echo sources. Conceptually, a short pulse signal radiated through a high gain phased array could be used to map the reflected fields by master scanning a volume in which the body is located. Resolution would ideally be as low as a few centimeters to provide for diagnostics as well as operational data, but even if resolution were as great as a few tens of centimeters, would still yield data for many applications. For one, the 3D reconnaissance (or perhaps target identification) radar discussed earlier would be provided with baseline data. Furthermore, if phase and amplitude

of echo from each sub-unit of a target were recorded for plane wave illumination, in principle, the scattering for any viewing range and/or illumination could be constructed for whatever application. Although the initial cost of such a facility might be high, the wide variety of uses for the resultant data should make a long term operation very cost effective. State-of-the-art in instrumentation should make this concept feasible.

Lastly we will discuss dynamic measurements. With space vehicles (satellites, re-entry vehicles) being singular exceptions for which huge national resources were expended to overcome an apparent technology gap, the state-or-the-art in dynamic measurements falls considerably short of current needs. Most facilities for measuring radiation or scattering from aerodynamic bodies (and there are not many such facilities) provide the most elementary information - largely smoothened data versus viewing angle (in 5° - 10° intervals) with some rough indication of amplitude fluctuation. In the latter, neither peak nor null values, nor fluctuation rates are necessarily exact due to instrumentation capability and measurement conditions, especially range limitations. There are no coherent systems which can provide doppler data on large bodies at satisfactory ranges, nor are there systems capable of good range and angle resolution. Again it is to be emphasized that space facilities can and do provide such data, but often these are not available for general use, they may be overdesigned in capability and yet too limited in frequency coverage, and lastly their operating costs may be beyond budgets of programs on aerodynamic vehicles. The latter is especially true in early stages of concept development.

It is well known that current operational systems (both friendly and hostile) employ coherent processing, doppler filtering, and like methods for manipulating scattered signal data to advantage. Despite this knowledge and the expectation that even more elegance is anticipated in the future, there is no facility to provide appropriate data on aircraft, chaff, decoys, or

similar bodies of great interest. Chaff in particular presents a problem because only through dynamic testing can the full impact of launch conditions, atmospheric effects, and element aerodynamics be observed. It is therefore essential that a measurement facility be implemented to provide coherency, non-ambiguous determination of amplitude fluctuation angular scintillation and doppler rates, high spatial resolution, and all the necessary monitoring capability for dynamic measurements of a wide range of target types. A broad range of operating frequencies must be available for gross spectral information as a minimum. Digital recording and processing is essential for data handling. Lastly, the site must not restrict drops of materials or flights of unmanned vehicles which are of interest. Ideally, the instrumentation would be transportable.

Without this capability, it is possible that advanced counter-radar programs will suffer seriously through inability to validate performance of the product. Recognizing the importance of the need, the Air Force Avionics Laboratory sponsored a program to define the basic design of such a facility (see AFAL-TR-74-54 "Chaff Cloud Signature II Measurements Program", Hycor Inc., August 1974, Contract F33615-73-C-1160).

Beyond the above needs in diagnostics, static measurements, and dynamic measurements, there are other questions which should be answered for the general advancement of scattering investigations. A major point which enters many discussions of how data should be taken and presented is that of a radar's response to a real-world echo signal. Almost invariably text book analyses deal in point sources, idealized echo spectra, etc. Clearly there is no single answer since signal processing is so variable, but realistic evaluation is needed on such questions as "where on a complex target does a leading-edge tracker track?" or "what statistical level of echo signal most determines

target detectability?". Beyond the implications to scattering investigations themselves, the answers have profound influence on critical problems such as design of electronic countermeasures.

In summary, this brief overview provides the rationale for additional (and unsatisfied) requirements for experimental techniques in electromagnetic scattering. Each of the areas discussed - diagnostics, static measurements, and dynamic measurements - lacks specific capabilities which impact either the understanding and control of scattering, or the provision of appropriate information for assessment of operational effectiveness. Advancements required in static and dynamic measurements are generally within state-of-the-art and need only financial support for implementation. Those for diagnostics may well need research before a feasible approach is identified for complex bodies.

After completion of this panel's report, Dr. Knausenberger of AFOSR suggested some additional areas of study: 1) extension of scattering experiments (as well as theory) to cases where the target is completely shielded or where metal targets are "penetrable"; 2) feasibility of new diagnostic techniques, e.g. (i) application of coherent optics techniques, (ii) speckle observation of properly scaled models, (iii) three-dimensional electric field observation by use of (luminescence) excitation in gaseous media around the scattering target.

PANEL ON APPLICATION OF MODERN MATHEMATICAL TECHNIQUES TO SCATTERING

Chairman: C.E. Baum, Air Force Weapons Laboratory.

The purpose of the panel on Application of Modern Mathematical Techniques to Scattering was to explore two items:

a. What are the problems to be solved (i.e., Air Force needs)?

b. What techniques might be developed in scattering technology to solve these problems, at least in part?

The chairman opened the panel by outlining its purpose and pointing to some of the general mathematical concepts, both analytical and numerical, that have some bearing on the panel discussion. It was noted that certain specialized topics would be treated at other specific times during the conference. The chairman then called on the panelists, consisting of Air Force and university representatives.

To present some of the Air Force needs the chairman called on William F. Bahret of Air Force Avionics Laboratory. With much stimulating presentation and discussion, several major needs were pointed out:

a. radar signature control,

b. reduction of coupling between antennas on aircraft,

c. understanding the radar cross section of antennas.

Haywood Webb of Rome Air Development Center then also presented some of the Air Force interests including:

a. necessary and sufficient conditions on scatterer shape and other structural characteristics for different scatterers to have the same backscatterer pole locations (perhaps with different residues) in the complex frequency plane (SEM);

b. improve the general theory of diffraction (GTD) for:

1. multiple scattering on a multi-edge body,

2. concave surfaces,

3. flat surfaces with inside angle bends,

4. vertices of two or more edges (diffraction coefficients);

d. properties of backscattered data which are orientation independent (other than the pole locations):

e. properties of composite materials which are being introduced into aircraft design including:

1. basic electromagnetic parameters,

2. shielding properties,

3. characteristics in conjunction with antennas,

4. radar reflectivity,

5. lightning protection,

6. precipitation static protection,

7. new radiation characteristics and radiator designs.

Prof. L.B. Felsen of Polytechnic Institute of New York addressed some of the problems from the point of view of possible new techniques. He felt that there were few obvious new techniques to apply of practical importance. However, because we have difficulties using the current tools, he thought that the EM community should actively explore what is going on in other disciplines from the point of view of finding techniques which might be usefully applied to electromagnetics. In this regard he suggested that there be meetings of EM specialists with people from other disciplines. These people should be willing to be exposed to other ideas so that all the disciplines benefit by borrowing from each other.

Prof. Ralph Kleinman of the University of Delaware raised several points:

a. Mathematical techniques not presently used in electromagnetics should be considered for such possible use, including:

1. optimal control theory (for boundary control),

2. approximation theory,

3. weak solutions and Sobolev spaces (including open surfaces, flush mounted antennas, and loaded scatterers with discontinuous impedance boundary conditions),

4. spectral theory of integral operators (for analytic continuation of low frequency expansions and for the singularity expansion method).

b. Investigation is needed into whether a target's natural frequencies of mechanical oscillation can be ascertained from the scattered electromagnetic field.

The audience also contributed a few observations. Prof. Raj Mittra of the University of Illinois observed that one must get steeped in the subjects before one can have the insights to apply new techniques. Prof. E.V. Jull of the University of British Columbia suggested that new experimental techniques were also needed. Prof. Piergiorgio Uslenghi of the University of Illinois at Chicago Circle suggested several things including:

a. application of graph theory,

b. more considerations in time domain,

c. applications of integrated optics,

d. basic studies of the electromagnetic properties of materials.

Reflecting on the course of the panel discussion as well as some of his thoughts in organizing the panel the chairman can make some observations. It may seem a truism, but worth stating anyway, that the important problem is to define the problem. Before the electromagnetic research community can attempt to solve a problem they must know what the problem is. This means that either the Air Force must pose problems to the researchers in well defined mathematical terms or the researchers will have to dig out the problems themselves by working on real Air Force system projects, or both. In general we can expect that only some of the right questions have been asked. The chairman has been somewhat

disappointed in that researchers in electromagnetic scattering seem reluctant to speculate, and wish to talk almost exclusively about things they have worked out in detail.

PANEL ON THE STATE OF THE ART OF SINGULARITY AND EIGENMODE EXPANSION METHODS

Chairman: C.E. Baum, Air Force Weapons Laboratory.

Preliminary to the panel was a set of four papers on the subject. The first invited paper by Profs. C.L. Dolph and R. A. Scott of the University of Michigan (each giving a part of the presentation) entitled "Recent Developments in the Use of Complex Singularities in Electromagnetic Theory and Elastic Wave Propagation" was a review of concepts related to the Singularity Expansion Method (SEM) as found in mathematics, quantum mechanics, and elastodynamics. This was an attempt to expose the conference participants to some things occuring in other fields of possible relevance to electromagnetic scattering. The second invited paper was that by the chairman entitled "Toward an Engineering Theory of Electromagnetic Scattering: The Singularity and Eigenmode Expansion Methods" which concerned the state of the art from the electromagnetic point of view.

There were two contributed papers. The first, presented by Dr. J.N. Brittingham of Lawrence Livermore Laboratory (coauthors Drs. E.K. Miller and J.L. Willows) entitled "A Technique for Obtaining Simple Poles from Real-Frequency Information" concerned the obtaining of natural frequencies from frequency domain (CW) data. The second presented by Dr. B.K. Singaraju of Air Force Weapons Laboratory (coauthors Dr. D.V. Giri and the chairman) entitled "Contour Integration Method of Evaluating the Zeros of Analytic Functions and Its Application in Finding Natural Frequencies of a Scatterer" concerned new efficient techniques for finding natural frequencies from zeros of denominators such as appear in the moment method (MoM).

Having set the stage with the more formal presentations involving some

reviews and some new developments, the panelists were asked to give some brief remarks. Eigenmodes were addressed by Dr. F.M. Tesche of Science Applications, Inc., Berkeley. He presented some numerical calculations of the eigenvalues (impedance form) of the integral equation for a thin wire in MoM form. The variation of the eigenvalues in the complex frequency plane showed the separation of the natural frequencies according to these eigenimpedances. Then Prof. D.R. Wilton of the University of Mississippi continued this discussion of eigenmodes with the example of the circular loop. He showed how the natural frequencies were grouped in this case and how the synthesis of natural frequencies worked in this case with the simplification afforded by the available analytic approximations for the circular loop problem. He also pointed out a way to synthesize the coupling coefficient by paying attention to the frequency derivative of the eigenimpedance and loading impedance.

Prof. C-T. Tai of the University of Michigan raised the question of computing zeros as well as poles in SEM. For driving point impedances, such as in the biconical antenna on which he was working, both are present and both should be characterized. He also raised the question of the significance of higher-order layers of poles and under what conditions they might or might not be present. Prof. Tom Shumpert of Auburn University could not be present due to an emergency and so forwarded some written comments for presentation by the chairman. He addressed the accurate calculation of the natural frequencies of scatterers. For this purpose he considered a perfectly conducting circular cylinder, near and parallel to a perfectly conducting ground plane. As the spacing from the ground plane approaches the radius the results become significantly in error if a uniform current distribution around the cylinder is assumed. However, by using a current distribution corresponding to a two-wire transmission line these errors appeared to be overcome.

Another subject for panel discussion was the determination of poles from experimental data. Prof. D.L. Moffatt of Ohio State University discussed the application of Prony's method to schemes of target identification. Various practical identification problems were pointed out including the problem of pole modification and closely spaced multiple targets. Dr. Andrew Poggio of Lawrence Livermore Laboratory also considered Prony's method for characterizing transient data, such as obtained at their Laboratory. He discussed some of the accuracy problems such as found in the higher order poles.

Prof. Raj Mittra of the University of Illinois made some general comments about some outstanding problems in SEM. He emphasized the coupling coefficients and their relation to the entire function, i.e., when is an entire function required? In this regard he presented some ideas about other ways to construct coupling coefficients involving the numerical and asymptotic behavior of the transform of the inverse of Green's function.

PANEL ON INVERSE SCATTERING

Chairman: V.H. Weston, Purdue University.

The inverse scattering problem is the characterization of the structure of an object or set of objects from scattering data.

The class of objects are as follows:

(1) Isolated simple objects with the following subclass of material composition:

(a) perfect conductors,

(b) dielectrics,

(c) composite materials and/or absorbers.

(2) Multiple objects or targets.

(3) Objects in a background of clutter.

The problem areas associated with inverse scattering are:

(1) The continued development of techniques or methods for describing the shape of a body, with the more refined details to some appropriate resolution.

(2) Means of description of what set an object belongs to, and techniques of discrimination between sets.

(3) The establishment of the minimum number of measurements necessary for the classification of a set.

(4) What set of shapes have the same class of scattering properties where the class is some prescribed set of measurements.

(5) The relationships between the natural resonances and the shape of a body, and the effect of the interaction of multiple objects upon resonances.

At the present time there are a number of groups in this country and abroad who are obtaining partial success on various aspects of realistic inverse scattering

problems. These advances are due in part to the fact that a theoretical groundwork has already been laid and is continually being expanded.

The panel recommends that all inverse scattering techniques that hold the promise of being fruitful be pursued, whether they be high-frequency, low-frequency, time-domain techniques, or otherwise. The various techniques will serve to complement each other. A phenomenological approach using single or multiple frequencies or the time-domain will help to define and resolve meaningful characteristics from those which are ambiguous or unwanted.

The panel recommends that a DOD Data Bank be established, to collect coherent data of the complex scattering matrix of isolated objects, multiple objects and objects in clutter. Such data is to be collected from measurements as well as from computations which are verified by experiments. Once collected, the data should be organized in a systematic manner. The National Data Bank should either generate the necessary data or contract it out. These data will be useful for people doing work in direct scattering as well as those doing work in inverse scattering. Persons having a need for the data should have access to it.

The priorities of the panel's recommendations are as follows:

(1) Establish a DOD Data Bank
(2) Investigate the inverse scattering problem for simple objects. The priorities in choosing the type of material are to be determined by Air Force needs. (The order of difficulty of the inverse problem for simple shapes as a function of material is as follows: (i) perfect conductor, (ii) dielectric, (iii) composite).
(3) Investigate the inverse scattering problem for multiple targets.
(4) Investigate the inverse scattering proglem for targets in clutter.

PANEL ON PROPAGATION IN RANDOM AND/OR NONLINEAR MEDIA

Chairman: N. Marcuvitz, Polytechnic Institute of New York.

The tasks addressed by this panel relate to the status, outstanding problems, and suggested methods of analysis in the general area of electromagnetic wave propagation. Because of insufficient time for discussion, the following comments are incomplete. As an overall recommendation, probably applicable to the other panels as well, it is suggested that meetings of this type should be held on an annual or bi-annual basis if it is desired to couple the academic and industrial community to the current status of problem areas of interest to the DOD.

On an overview note, the following propagation problems arising in communication, sensing, and power transfer applications, were considered in the panel discussions:

A) Atmospheric Turbulence (Optical and Microwave)

Further research is required when the average background and correlation properties of the atmosphere are both inhomogeneous and nonstationary, also when the incident signal is randomly modulated by noise sources. Of particular importance for sensing applications are statistical analyses of received phase fronts, scintillation analysis, and effects of strong atmospheric fluctuations. An open problem relates to methods of analysis when scattering particle size is comparable to the sensing wavelength.

B) Ionospheric Scintillations (Microwave and VHF)

Forward scattering analysis appears to be in a satisfactory state, for the most part, but many difficulties are associated with the self-consistent calculation of the correlation properties of density fluctuations in various layers of the ionosphere.

C) Scattering From Rough Surfaces

Most of the difficulties center around methods of analysis of scattering from inhomogeneous and nonstationary types of discontinuous curved surfaces as a function of size parameters.

D) Random Discrete Scatterers

Problems remain for random distributions of arbitrary discrete obstacles when boundary layer effects are important and when the systems are velocity dependent. Also more accurate methods of calculations of 2 point and higher correlation properties of the field are required for cases where the refractive index of the scatterers differs markedly from the imbedding medium and when the scatterer size is not large compared to wavelength.

E) Waveguide Propagation

Many facets of the analysis of propagation in a waveguide wherein the medium and walls have inhomogeneous statistical properties pose unresolved problems. The general area of diffraction in random media has not been really addressed.

F) Nonlinear Wave Propagation

Ionospheric modification at high microwave powers, thermal blooming effects (and corrections) associated with high power laser propagation, and also decoupling effects of blow-off plasma in high power energy transfer are among a series of nonlinear problems that require self-consistent methods of solution. The propagation of high power laser beams through dense clouds and mists by creation of optical channels arising from radiation-induced evaporation of water drops poses a self-consistent problem of considerable interest for optical telecommunications.

On a more substantive and illustrative note, item A) on turbulent

electromagnetic propagation in a neutral atmosphere, was the only area the committee discussed in any detail and even this was incomplete because of insufficient time. More complete theoretical and experimental information is required on the average and 2 point correlation properties of the atmospheric dielectric constant. Of particular interest are statistical inhomogeneous and non-stationary behavior especially in the low frequency range wherein "frozen in" assumptions are frequently used. For the case of an extended inhomogeneous and non-stationary atmosphere the problem is primarily that of determining the statistical properties of a propagating electromagnetic wave such as: average complex amplitude and phase as a function of slow space and time variables, the 2 point mutual coherence, as well as amplitude and phase correlations, the 4-point correlation in real space-time and in both spectral space and slow space-time, etc. The fourth-order moment (intensity correlation) is of particular importance in the understanding of scintillations caused by an external medium. The nature of the probability density function - Log Normal, or Gaussian, etc. - effects of slow space and time initial and boundary conditions on wave turbulence problems are areas in need of further study. Backscattering in a strong fluctuation region is a problem that requires a better method of analysis. Depolarization and cross-field polarization methods of analysis are of importance particularly for propagation through rain (primarily at millimeter wavelengths) wherein scatterer size and wavelength are comparable.

The above problems evidently fall into two broad categories:

1) Obtain experimentally or derive theoretically, data on the statistical distribution of scattering structures in a background medium and determinedefining equations satisfied by all n-point moments of the wave field.
2) Find methods of solution of the n-point moment equations (because of the lack of time this last category was not discussed).

PANEL ON REMOTE SENSING OF ENVIRONMENT

Co-Chairmen: A. Ishimaru, University of Washington.
J.R. Wait, NOAA, University of Colorado.

Remote sensing of the earth environment by electromagnetic scattering technique has become increasingly important because it provides a new tool in the study of the structure of the environment and its effects on communication, target detection, classification and tracking. In general, electromagnetic remote sensing requires the following considerations:

(1) Determination of relationships between the desired environmental information and its electromagnetic properties.

(2) Determination of the relationships between the electromagnetic properties of the medium and the measurable quantities.

(3) Choice of appropriate sensors and measurement.

(4) Extraction of the desired information from measured data by inversion, iteration or other techniques, and error analysis.

In this report, we present a brief account of the above areas with emphasis on our present state of the art and future needs. We consider the following three areas of the environment: atmospheric and ionospheric environment, ocean and land surfaces, and subsurface environment.

The relationships between the environmental information and its electromagnetic properties have been studied extensively. In the atmosphere, velocity field, temperature, humidity, electron density, geomagnetic field, rain drop sizes, fog, etc. have been related to the refractive index field, the absorption and scattering characteristics, etc. For ocean and land surfaces, sea-state, foam, spray, white cap, ice type, snow, wind velocity, vegetation, trees foliage, crop type, growth stage, soil type, etc. have been related to the scattering characteristics of the surface. For subsurface environment, temperature, pressure, minerals, ice, moisture in rocks, etc. have been related to conductivity,

dielectric constant, and permeability of the medium. These studies should be extended to cover a wide range of frequencies, polarization, incident angles, and various media. It is desired to conduct further study systematically so that the results may be applicable to a wide range of practical problems. For example, very little is known about the frequency dependence of the constitutive properties of geological materials. Such dispersive effects play a major role in determining pulse shapes for through-the-earth transmissions.

The determination of relationship between the electromagnetic properties of the medium and the measurable quantities requires extensive theoretical study. In the atmosphere, most theoretical studies are based on single scattering theory. They have been used for optical, microwave and acoustic radars in weather forecasting, weather modification, pollution studies, storm warning, air traffic safety, and other applications. However, there are situations such as dense clouds and heavy rain which require a study of multiple scattering effects. Also, radiometric techniques of determining rain attenuation, temperature, etc., need to be expanded to include multiple scattering. In addition to single scattering theory normally used in pulse studies, there is a need to include pulse propagation for multiple scattering in strong fluctuation regions. In ocean and land surfaces, most studies are made on the basis of perturbation theory and Kirchhoff approximations. In some cases, such as grazing incidence, strong interaction between waves and surfaces occur similar to multiple scattering effects, and this needs to be examined more fully. The interaction of the surface and the incident pulse needs to be clarified. Effects of antenna to medium coupling, surface illumination, spatial and temporal surface variations need to be studied further.

In the subsurface environment, considerable studies on subsurface waveguides, pulse propagation, and effects of inhomogeneities have been made.

However, further studies are needed on the scattering from objects or inhomogeneities imbedded in homogeneous or inhomogeneous medium, either deterministic or random. This study must be extended beyond the first order perturbation solution usually used at present. It should also include the effects of anisotropy and polarization. Of particular interest is the scattering of voids and air-filled tunnels in the earth from surface based probes.

Many experimental techniques have been used in remote sensing, including lidars, radars, acoustic sounders, scatterometers, altimeters, radiometers, imaging radars, holographic techniques, etc. New techniques and sensors may be needed including data processing capabilities.

Extraction of the desired information from the measured data is relatively simple in some cases such as radar observation of the atmosphere. However, in many cases the measurement error is greatly amplified in the process of extracting the desired information. This is an ill-posed problem and the use of deterministic or statistical inversion techniques are needed to obtain a stable solution. This also yields an estimate of the errors involved. Recently a great deal of progress has been made on various inversion techniques. However, there is a need to further refine or simplify the inversion theory so that it can be more readily applicable to a variety of practical problems.

We note here that great progress has been made in other countries, particularly in the Soviet Union, on the multiple scattering theory and the inversion theory. In terms of the number of scientists and their research outputs, the Soviets are very much on a par with the U.S. and in some areas they are clearly ahead. It is desired that concerted efforts be made by U.S. scientists to maintain or gain a leading scientific role in this area.

It should be recognized that his report was prepared with inputs from individuals who attended the National Conference and who are interested in remote

sensing of the environment. Time limitation did not permit us to obtain advice from many other experts in remote sensing who could not attend the National Conference. The reader of this report should also be aware of the excellent report on "Remote Sensing of Observables in Geophysics" by J.R. Wait in the Proceedings of the NSF workshop on "Future Directions of Electromagnetics of Continuous Media", December 1972. Many of the recommendations contained in that report are still relevant today.

PANEL ON ANTENNAS

Chairman: C.T. Tai, The University of Michigan.

The panel members contacted several participants at the Conference asking them or their colleagues to prepare a list of problems in the antenna area which are considered to be significant for the future advancement of antenna theory and technology. Most of the people contacted by the members of the panel have graciously responded. The problems or the opinions expressed by these personas and by the panel members are listed below.

A. Research Areas in the Field of Antennas

Giorgio Franceschetti, University of Illinois at Chicago Circle.

1. Transient radiation from antennas

It is rather surprising that rigorous analytical solutions for transient radiation from metal antennas are almost non-existent. Practically, only the infinitely long cylindrical antenna has been thoroughly studied. On the contrary, a large and steadily increasing body of papers is being published on numerical methods of solutions. Accordingly, it seems to be rather important to have some canonical problem of transient radiation for which a rigorous solution is available. Possible cases are the following:

i. the spherical antenna
ii. the spheroidal antenna (limiting case: the thin wire)
iii. the biconical antenna.

2. Radiation from truncated structures

The problem of transient radiation from truncated guiding structures, as open ended waveguides and horns, is certainly most important from the application point of view. When the guiding structure is used as a primary radiator of a reflector-type antenna, it would be highly desirable

to have reliable expressions for the radiated field in a wide angular variation of the phase center of the field. It is rather obvious that the aperture integration method coupled with Kirchhoff approximation is a rather unsatisfactory approach to this problem, since its validity is limited to small angular region close to the axis. New approaches should be developed able to take into account:

i. aperture size and form,

ii. flare angle,

iii. rim loading.

3. Transient radiation from apertures

Coaxial apertures could be a rather effective way for radiating transient signals, since the pulse propagating along the cable is not deformed along its way to the truncated end. Rigorous theory of transient radiation can be developed once a rigorous steady state solution is available (see sec. 2). The theory should take into account:

i. coaxial aperture geometry,

ii. interaction between inner and outer rim.

4. Timed arrays

The theory of phased arrays is now well established. In a crude way, one can say that the radiation diagram can be shaped and steered by controlling the phase distribution across a number of (essentially monochromatic) radiators. If pulsed radiators are used instead of monochromatic ones, the radiating properties of the array can be controlled by changing the time distribution of radiating pulses across the radiating elements. This type of array can then be named "timed array".

It is obvious that the design of a timed array should take into major consideration the coding of the signal. Major areas of study seem

to be the following:

i. analysis of array performance,

ii. synthesis procedures,

iii. influence of the coding in the array performance.

5. Antenna and environment coupling

The study of transient radiation in dispersive media is important from academic and applications point of view as well. New ways of environmental diagnosis and monitoring could be anticipated when the transient radiation mechanism is well understood. Areas of study seem to be the following:

i. spherical antennas,

ii. spheroidal antennas,

iii. loop antennas,

iv. biconical antennas

in dispersive lossless and lossy media.

B. Some Important Antenna Problems

Y.T. Lo, University of Illinois at Urbana-Champaign.

1. Multiple-beam antennas
2. Aberration-corrected reflectors and lenses
3. Anisotropic effect of artificial dielectrics and method of its correction in lens design
4. Development of truly isotropic and polarization-independent artificial dielectrics
5. Theory of artificial dielectrics with randomly distributed scatterers
6. Method for producing high uniformity of bulk random artificial dielectrics
7. Development of reliable low loss and low cost phase shifters for millimeter and microwave phased array application

C. <u>Some Future Directions for Antenna Research</u>

P.E. Mayes, University of Illinois at Urbana-Champaign.

The most obvious ones are associated with the recently developed technology of computers and solid state. Continued efforts in numerical analysis of antennas and antenna systems should include reformulations of the mathematical models for more efficient computation. While recognizing that the results will be short of miraculous, the merging of solid-state materials and radiating elements should continue to produce some useful results. The combination of electric (dipole) and magnetic (loop) elements in a single antenna provides a method of producing directive gain in a small antenna with slowly-varying impedance. Such antennas may work well in the standing wave field caused by multiple reflections and more work is needed in evaluating antenna performance in non-ideal conditions.

D. <u>Required Antenna Research</u>

Gordon A. Taylor and Wayne S. Hammond, Boeing Aerospace Company

1. <u>Low RCS concepts</u>

The design of aircraft to achieve some desired level or character for the radar cross section (RCS) may ultimately be governed by the scattering from the various antennas on-board. Some of the more prominent problems in this area are listed below.

i. Broadband Antennas - 1 to ? Octaves:

Low Gain Fixed Beam - These antennas are frequently employed for ECM systems and are not amenable to treatment with any "tuned" or narrow band treatments. Techniques such as aperture shaping, edge treatments, active (pulsed) aperture control and termination impedance modifications are among the methods which should be explored.

Steerable - These antennas are similar to the above but are usually higher in gain and consequently may be steered or a switch multiple antenna scheme used. The design problems are compounded if any phase or frequency scanning concepts are used.

Monopulse - There are several applications for broad-band DF or homing antennas on low RCS vehicles. There requirements are not incompatible but more extensive research needs to be conducted to examine truly low RCS concepts suitable for multi-octave operation.

ii. Narrowband Antennas (<< 1 octave):

Arrays - The forward aspect scattering for many military aircraft may be significantly influenced by the presence of large array antennas. Methods to estimate and control the RCS from the various array types must be devised.

2. <u>General antenna problems</u>

The following antenna problems have been identified as in need of solutions:

i. High Gain Hardened Antennas - What is the best technique of hardening high gain antennas?

ii. Large Aperture Deployable Reflectors - What are the limitations on sizes of deployable reflectors such as:

a. Geodesic truss (General Dynamics)

b. Umbrella (Harris Radiation, Inc.)

c. Flexible Rib (Lockheed Missiles and Space Division)

iii. A Ring Array has the advantage of being low profile with ≈ 99 percent coverage to -9 db. What techniques can be employed

to broadband this capable antenna system?

iv. Investigate techniques of providing constant beamwidth radiation from a large aperture broadband antenna.

v. Develop a broadband, conformal, high accuracy, anti-radiation homing antenna for hypersonic missile applications. Determine performance effects due to thermal ablation effects as a function of frequency and look angle.

vi. Correlate near field-far field pattern measurement by analysis. Establish accuracies required and fundamental limitations due to aperture size, probe, coupling, etc.

vii. Analyze the best way to provide side lobe level control while scanning large aperture beams.

viii. What techniques may be used to harden satellite antennas against laser radiation?

ix. What techniques can be used to compensate for in-flight distortions (due to thermal and solar winds) of large aperture antennas?

x. Prepare a complete set of scalar design curves - include gain, beamwidth, and side lobe level vs. dimensions.

xi. Is there a fundamental limit of gain, bandwidth, and electrical size? Is there a way to look at a given set of requirements to determine if each is achievable?

xii. Examine the null sharpness and component bandwidth impact on adaptive array antenna for ECCM or clutter rejection.

xiii. Develop analysis techniques for arrays with strong element coupling for high efficiency multi-beam systems.

xiv. An investigation of near-field sidelobe activity and its relation to scattering from surrounding structures, for different antennas.

xv. Develop multi-purpose antenna concepts suitable for reducing the total number of antennas on an airplane.

E. Suggested Topics in Basic Technology in the Field of Antennas

R.W.P. King, Harvard University,

L.C. Shen, University of Houston,

D.C. Chang, University of Colorado,

R.W. Burton, Naval Postgraduate School.

1. Receiving and scattering properties of missile-like structures.

When a possibly electrically long metallic structure is exposed to an incident electromagnetic field, possibly significant fields can penetrate into the interior through slots or other apertures including joints. These may be most intense when the field is far from normal incidence. This problem should be studied over a wide frequency range.

2. Antennas for aircraft designed to have the required directional properties with a minimum contribution to the scattering cross section.

3. Bare and insulated antennas in and over the surface of the earth, sea, etc., as directional transmitters, receivers and scatterers. Specific applications include directional subsurface and Beverage-type communication systems and scattering from low flying aircraft when illuminated from above.

4. The generation of prescribed steady-state and transient fields in test areas of simulators. The generation of a plane-wave front is of particular interest.

5. Transmitting and scattering properties of moving and vibrating metal structures.

6. Antennas on aircraft made of composite material. This is of particular interest in conjunction with the commonly used slot antennas.

7. Transient properties of antennas including antennas with junctions.

F. <u>Recommendations for Antenna Research</u>

R.J. Mailloux, Electromagnetic Sciences Division, Deputy for Electromagnetic Technology, Rome Air Development Center

1. Interaction of antennas with their environment; the earth, aircraft, spacecraft, man-pack, conformal antennas.

2. Mutual coupling and edge effects; analysis of finite arrays.

3. <u>Limited sector scanning arrays</u>

   i. Synthesis of overlapped subarray techniques for low sidelobes and limited sector scanning

   ii. Antenna techniques for limited sector scanning

   iii. Reflector and lens techniques, synthesis, and matching for low sidelobes with limited scan capability.

4. Studies of basic new elements and their scanning properties (microstrip, strip-line).

5. Studies of elements with dual and multiple frequency capability. Studies of scanning properties.

6. Techniques for adaptive control of radiation patterns, null steering, S/N optimization, etc.

7. Antenna-radome studies including integrated design approaches for antennas and arrays in cylindrical, spherical, conical and other characteristic shapes.

8. Spatial filter studies for sidelobe suppression. Synthesis using layered dielectric radomes and metallic grating structures.

9. Studies of broadband antennas and research into time domain analytical techniques for antennas and systems excited with short pulses.

10. Research into ultimate achievable sidelobe levels as a function of antenna type and configuration as well as array size, tolerance and phase control variation effects and the influence of mutual coupling.

11. Studies of low-sidelobe multiple beam synthesis. Studies of multiple beam synthesis with sidelobe constraints over limited sectors. Application to satellite antennas illuminating earth.

12. Studies of the interrelation of feed switching network hierarchy and complexity vs. the number and flexibility of multiple beams that can be formed.

13. Studies of design and construction techniques for low cost integrated antennas, especially array element-phase shifter combinations that are produced by photolithographic techniques.

G. Needs for Radiation and Scattering Prediction Connected with Antennas

William F. Bahret, Air Force Avionics Laboratory,
Air Force Wright Aeronautical Laboratories

This letter is to document needs for radiation and scattering prediction connected with antennas. The viewpoint here is that of a direct user, as well as that of an organization which provides technical support and consultation to government and industrial groups responsible for major system design. A non-trivial consideration in the work of the latter groups is that prediction methods must be amenable to use by personnel far removed from the academic dedication to excellence in a relatively narrow field.

Needs for prediction of antenna radiation range from patterns for an isolated element to those of the most intimately coupled element/vehicle

geometries. ECM and low frequency antennas being generally low gain types, share the problem that the host vehicle exerts strong influence on radiation from the ensemble. Therefore, optimizing the choice of antenna and location on a body involves the iteration of both. This is far easier and faster, in principle, through computational techniques, whatever they may be.

Another need is for prediction of mutual coupling effects between antennas on complex bodies. Understanding and control of coupling is frequently the dominant consideration in ECM systems which must receive and retransmit a broad range of hostile signals, as an example. Yet most design is done on a cut-and-try empirical basis today. Needless to say, the development of materials and techniques for control of coupling has suffered in the process. Not to be overlooked is the lack of confidence which system designers have in such an unpredictable "art".

Last but not least, the radar scattering from antennas must be predicted. Clearly arbitrary illumination - frequency and polarization - as well as arbitrary viewing angle are involved. Because of the wide range of frequencies which are of interest (100 to 20,000 MHz), antenna size varies from very small to very large in terms of wavelengths.

At higher frequencies, where lobe structure is reasonably fine, the first priority is to determine median (fifty percentile) values of radar cross section over say, five to ten degree intervals of viewing angle. At the low end of the scale, complete pattern detail is necessary since a single lobe may cover many degrees. Of course, a detailed pattern is the ultimate desire in either case.

Predicting scattering is essential to the increasingly important requirement for signature control. Beyond the immediate use for selection

of antenna types which inherently provide lower echo, prediction capability will also permit design of new antennas which simultaneously satisfy both radiation and reflection requirements.

H. Some Outstanding Problems in Antennas

C.H. Walter, The Ohio State University

1. Antenna shape synthesis

Directly solve for an antenna geometry that satisfies a specified set of characteristics, e.g., bandwidth, efficiency, size, etc.

2. Broadband, dispersionless antennas

New concepts for low loss, dispersionless antennas are needed for time domain systems.

3. What are fundamental limitations of a small antenna when in the presence of a support structure or nearby material body? Antenna on a composite material aircraft is a good example of a new problem.

4. Optimization of excitation of a given structure, such as an airframe.

Develop a procedure for selecting the best element type, number of elements, and locations of elements to excite a given structure to achieve a given set of specifications.

I. Basic Antenna Research

Chen-To Tai, The University of Michigan

1. Transient response of antennas

Canonical problems: biconical antenna, waveguide terminated by conducting screen.

2. Characteristics of antennas in the presence of lossy spherical earth.

Fock's theory should be delineated into a more practical form.

3. Finite methods applied to EM boundary value problems

The recent work of K.K. Mei has opened up a new area in EM research. The advances of sparse matrix techniques could aid considerably in the development of this research.

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